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ATS-6 MM-WAVE PROPAGATION EXPERIMENT
NAS5 - 20504

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Karl C. Davis
Philip A. Ekstrom
Battelle, Pacific Northwest Laboratories
Richland, Washington 99352

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

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15. Supplementary Notes

16. Abstract

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PREFACE

OBJECTIVE

The objective of the ATS-6 millimeter-wave propagation experiment is to characterize the Satellite-Earth propagation path at 20 and 30 GHz and correlate its properties with observable radiometric and meteorological phenomena. This information will be used as an aid in designing satellite-ground communication links at these frequencies.

SCOPE OF WORK

A 20 GHz receiver system, incorporating a radiometric receiver operating near 20 GHz, was constructed and operated in a 30-ft Cassegrain antenna system to directly measure attenuation of signals from the ATS-6 satellite. The system began to record received signal strength, radiometric sky temperature and precipitation rate simultaneously in March 1975. ATS-6 was relocated 3 months later, in June 1975, and radiometric sky temperature measurements related to precipitation were continued through August 1976. Fourteen hours of satellite signal attenuation data and more than 10,000 hours of radiometric sky temperature data were analyzed to relate Space-to-Earth path attenuation to local precipitation.

CONCLUSIONS

Weather conditions producing attenuation greater than 5 dB on a Space-to-Earth path at 20 GHz will probably occur less than 1 hour per year at the arid, eastern Washington State study site. Therefore, weather could be expected to interfere with 20 GHz satellite communications at this site for only a few hours per year, if antenna surfaces were kept clear of snow.

RECOMMENDATIONS

Further atmospheric path attenuation studies for regions of low precipitation intensity are probably needed only 1) for much higher operating frequencies, or 2) where extremely low probability of outage is required.

CONTENTS

FIGURES

FINAL REPORT ON BATTELLE-NORTHWEST'S PARTICIPATION IN THE ATS-6 MILLIMETER-WAVE PROPAGATION EXPERIMENT

INTRODUCTION

Battelle-Northwest's participation in the ATS-6 Millimeter-Wave Propagation Experiment was designed to determine the effect of Pacific Northwest weather on Satellite-to-Earth propagation at 20 GHz. Battelle Observatory has a 30-ft (9.1 m) diameter Cassegrain antenna system (Figure 1) located in the southeastern part of Washington State on the Energy Research and Development Administration's Hanford Reservation. The antenna is located near the top of a 1,060 m ridge close to the Observatory's optical astronomy and geophysical observing equipment. The site was chosen for minimum meteorological interference with millimeter-wavelength radio astronomical observation, and in particular for its low level of precipitation. The region receives an average of about 160 mm total precipitation per year.

INSTRUMENTATION

The major instrument used in this experiment was a 20-GHz receiver-radiometer system installed on the 30-ft antenna. The system measured received 20-GHz carrier level and radiometric sky temperature simultaneously in the same antenna pattern at similar frequencies. A single balanced diode mixer was used for both purposes. The mixer input port was switched between the antenna and an ambient temperature waveguide termination at a 1 kHz rate. A photograph of the antenna-mounted receiver radiometer unit showing most of the RF components appears as Figure 2; Figure 3 is a block diagram of the parts. A single IF preamplifier fed a power splitter and filters to define separate carrier and radiometer IF channels. The carrier IF system had remotely switchable filters defining passbands of 60 MHz ± 13, ± 2.5, and ± 0.5. The radiometric IF passband was fixed at 340 to 380 MHz. No RF preselector was used so both channels were double sideband. The local oscillator was set to 19.940 GHz to put the 20-GHz signal in the center of the carrier IF passband. Figures 4a and 4b show the frequencies used.

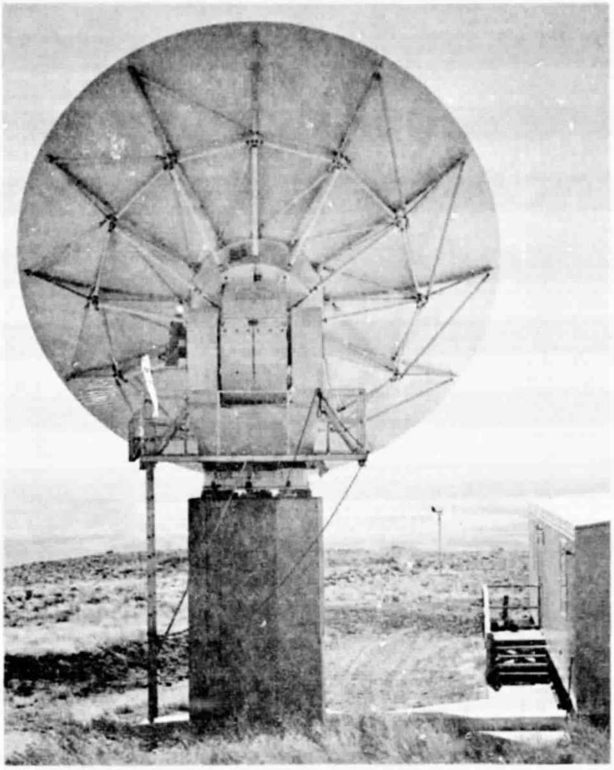


FIGURE 1. Battelle's 30-ft Antenna Pointing Approximately at ATS-6 Look Angle (rain gauge is below anemometer at lower right)

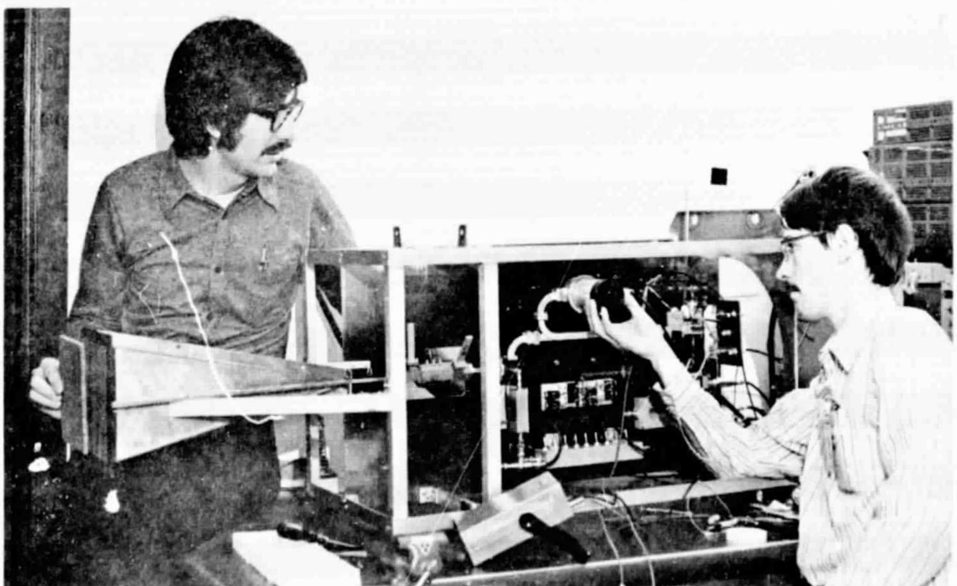


FIGURE 2. Antenna-Mounted RF Package

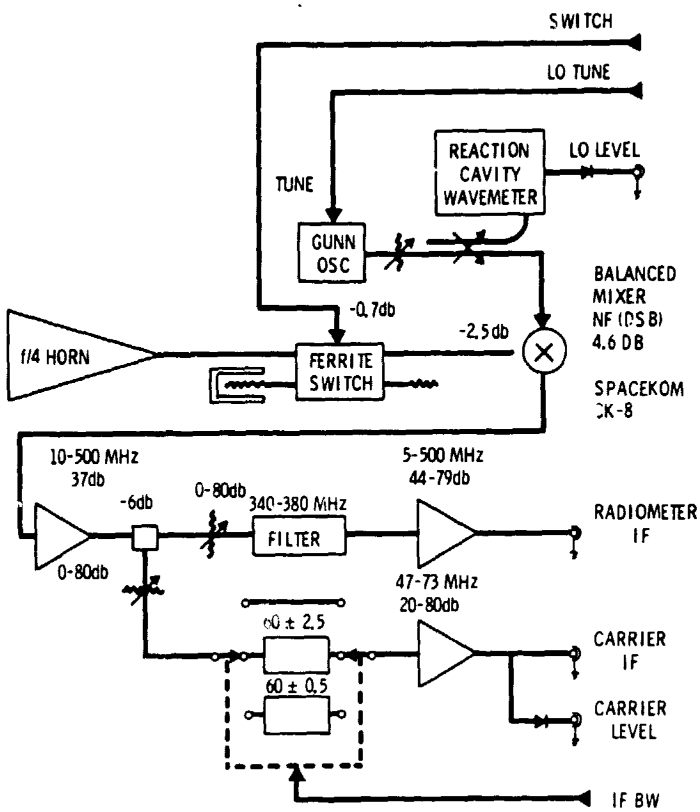
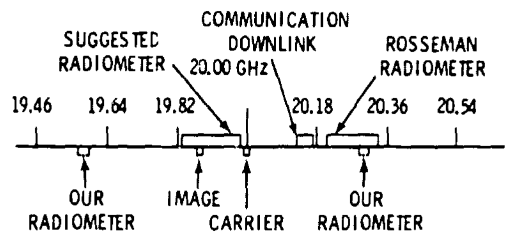
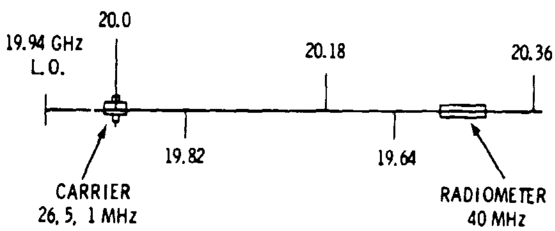


FIGURE 3. Receiver Package



a. Multi-tone Spectrum



b. Spectrum Folded by Mixer

FIGURE 4

Carrier level was measured by a wide dynamic range (30 dB) video detector and a 1-kHz-tuned amplifier-rectifier feeding a logarithmic amplifier and recorder. The carrier amplifier channel bandwidth used was 1 MHz and the post detection-tuned amplifier bandwidth was 20 Hz. Computed fade margin for the ATS-6 20-GHz transmitter using the parabolic antenna was approximately 50 dB for this configuration for unity signal-to-noise. The RF switching, AC measurement technique actually determined the difference between total power from the ambient temperature waveguide load in a 2-MHz passband and the 20-GHz signal. The computed signal-to-comparison-noise ratio was 30 dB. We would like to point out that this level of performance was achieved without a high-stability local oscillator or a phase-locked receiver; signal modulation was produced by the ferrite switch.

The radiometer IF channel output was detected and synchronously rectified to measure the difference between radiometric sky temperature and ambient waveguide load temperature. The difference was recorded on a second channel of the data recorder.

A tipping bucket rain gauge with heated collecting funnel was used to determine precipitation intensity. The rain gauge was located about 100 m from the antenna in an open area. Each bucket tip, representing 0.01 in. (0.25 mm) of water, was recorded along with the 20-GHz signal level and sky temperature. Additional instruments were provided to measure wind speed and direction, relative humidity, temperature, and barometric pressure. A block diagram of the control room equipment appears in Figure 5.

OPERATING PROCEDURE

The receiver-radiometer system was operated almost continuously throughout the experiment with the antenna pointed at the zenith. To make 20-GHz path attenuation measurements, the look angles for the appropriate time interval supplied by the National Aeronautics and Space Administration were entered in the tracking computer and the antenna was slewed to the designated initial position. The computer interpolated linearly between provided values to update the antenna position every 60 seconds. At the start of measurements,

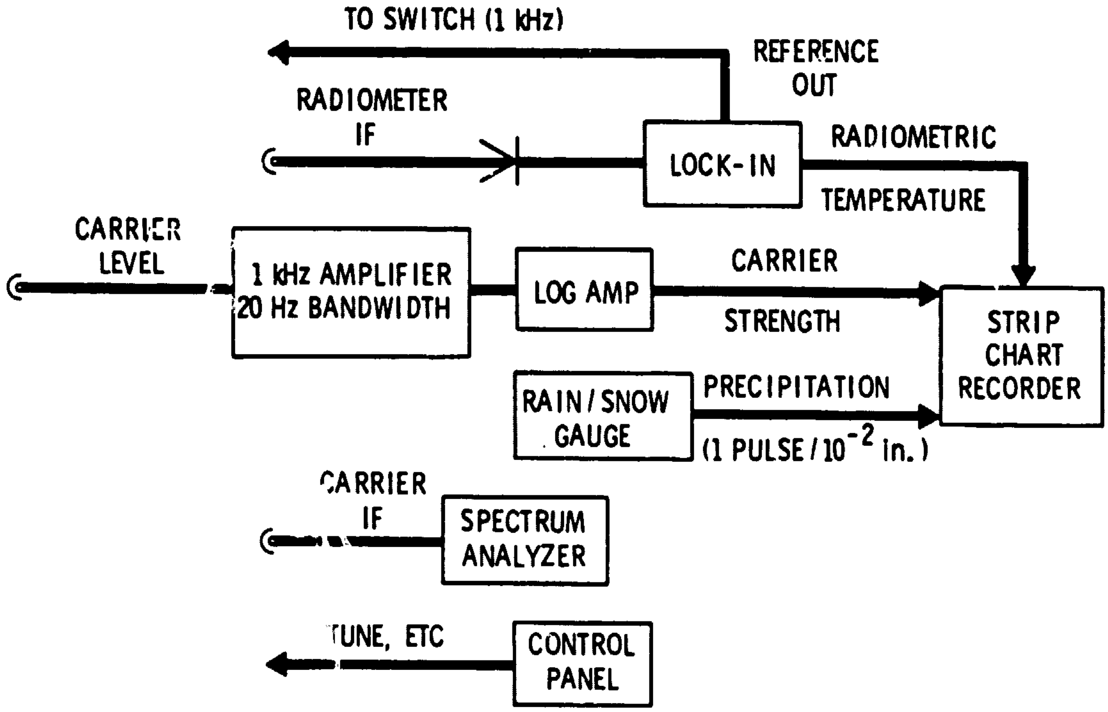


FIGURE 5. Control Room Equipment

the antenna position was adjusted manually to "peak" received signal strength. The local oscillator was tuned manually, if necessary, to center the received signal in the 60-MHz carrier signal IF channel. This manual tuning procedure, using a spectrum analyzer to locate the received signal, was the weakest link in the acquisition procedure. It was found that the signal margin for acquisition was approximately 30 dB at the most favorable satellite pointing.

RESULTS

All components were installed by March 19, 1975, and the first attempt at satellite acquisition on March 20 was successful. Routine operation began with a clear weather calibration March 21 and continued until loss of satellite June 3. Weather at the site was slightly drier and cooler than normal for this time period. Average total precipitation for the period is 28 mm, and 25 mm was measured this year.

20-GHz ATTENUATION

The 20-GHz transmitter was observed for a total of 14 hours. There was measurable precipitation (i.e., intensity greater than 0.3 mm per hour) during approximately four of these hours. The highest intensity precipitation through which 20-GHz signal attenuation was measured was wet snow equivalent to 1.5 mm of water per hour. No significant attenuation (i.e., greater than 1 dB) was observed which could be attributed to atmospheric absorption or scattering. Attenuation exceeding 10 dB and radiometric sky temperatures approaching ambient, above 250 Kelvin, were observed on this occasion. However, this occurred half an hour to an hour after passage of the precipitation and coincided with the melting of snow on most of the reflector surface. Similar attenuation and sky temperature were observed on another occasion following snow and coinciding with the melting of snow on the antenna. Substantially identical behavior of measured zenith sky temperature occurred on a third occasion about an hour after a light fall of wet snow. We therefore concluded that the observed high attenuations were due to wet or melting snow on the antenna primary reflector and/or feed cover, rather than atmospheric path attenuation.

RADIOMETRIC SKY TEMPERATURE

Observations of radiometric sky temperature at 20 GHz continued from March 1975 through August 1976, providing more than 10,000 hours of data relating measured sky temperature to locally observed precipitation. From March 1975 through February 1976 the receiver was operated in the 30-ft antenna described previously. Most of this operation was untended, with the antenna stowed in the zenith-pointing position. On several occasions in the summer of 1975 during storm activity, the antenna was pointed to representative ATS-6 look angles for sky temperature measurements at 30° elevation angle. Appreciable observing time was lost in the winter months of 1975-76 due to equipment failures, inaccessibility of the site due to heavy snow conditions, snow on antenna surfaces resulting in very high indicated sky temperatures for extended periods, and inability to provide detailed regular attention to the operation of the equipment.

In March 1976 the receiver was removed from the 30-ft antenna, modified, and installed at the main observatory building. The horn that had been used as a feed for the 30-ft antenna became the receiving antenna, giving a 15° beam at full width between 10 dB points. The horn axis was pointed approximately at ATS-6 look angles for the site, 30° elevation, southeast, with the beam passing over the rain gauge, which was about 0.7 km from the new receiver location. Radiometric sky temperature measurements were made for approximately 5,000 hours in this configuration (March 1976 through August 1976) with rain rate and relative humidity recorded simultaneously. The receiver system was checked frequently and calibrated weekly so essentially continuous, reliable data are available for this period.

During radiometer calibration, a hand-held piece of carbon-loaded foam absorber was used to establish the 300 kelvin point on the radiometer temperature scale. Clear blue sky was used to establish the 25 kelvin point. A path attenuation scale was derived from observed radiometric temperature by modelling the atmosphere as a 300 kelvin grey-body absorber of varying opacity viewed against a cold background. An observed temperature T was taken to imply a path attenuation in db relative to clear-sky conditions given by $A(db) = -10 \log_{10} \frac{300 - T}{300 - 25}$.

Only one anomalous occurrence was recorded, an attenuation greater than 10 dB which occurred during one early morning in March. The sky was clear and the high attenuation is believed to be due to heavy frost or dew on the Teflon window of the feed horn.

Precipitation for the period March 1975 through August 1976 was 90% of that expected from historical records. Figure 6 shows actual monthly precipitation totals and mean values based on 20 years' previous observations. August 1975 had much more precipitation than usual but there were no observed intervals of high precipitation intensity. The first half of 1976 was drier than usual but August was exceptionally wet.

We were fortunate in having two instances of very intense precipitation for this area, approximately 1 in. per hour, while the receiver system was operating.

In July 1975 there was a short period of heavy rain. The 30-ft antenna was pointed to 30° elevation 120° azimuth, representative of ATS-6 look angles

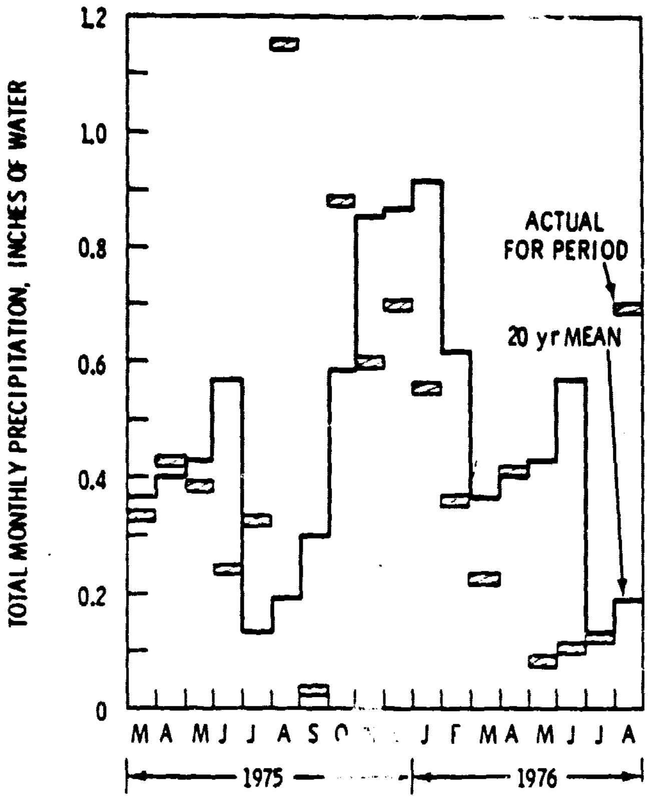


FIGURE 6. Actual Monthly Precipitation Totals for 1975-1976 Compared with 20-Year Mean Totals

and, in this case, the direction in which the storm appeared most intense by visual observation. Peak rain intensity measured at the antenna site was 0.06 in. in 4 minutes (approximately 22 mm per hour). This coincided with a measured radiometric sky temperature of 180 Kelvin, implying atmospheric attenuation of 4.6 dB.

In August 1976 a rain intensity greater than 25 mm per hour was observed for a 20-minute period. During the accompanying storm, radiometric sky temperature measured in a 15°-wide beam at 30° elevation indicated atmospheric attenuation greater than 3 dB for 32 minutes and greater than 6 dB for approximately 5 minutes. This was an unusually intense rain for this area. Climatological records from the Hanford weather station suggest that a similar storm will occur only once in 5 years (see Appendix).

Figure 7 is a reproduction of the data chart for this event. The upper trace is radiometric sky temperature with atmospheric attenuation values shown. The center trace is local relative humidity. The lower scale is the rain gauge record. Each change in pen position represents 0.01 in. of precipitation.

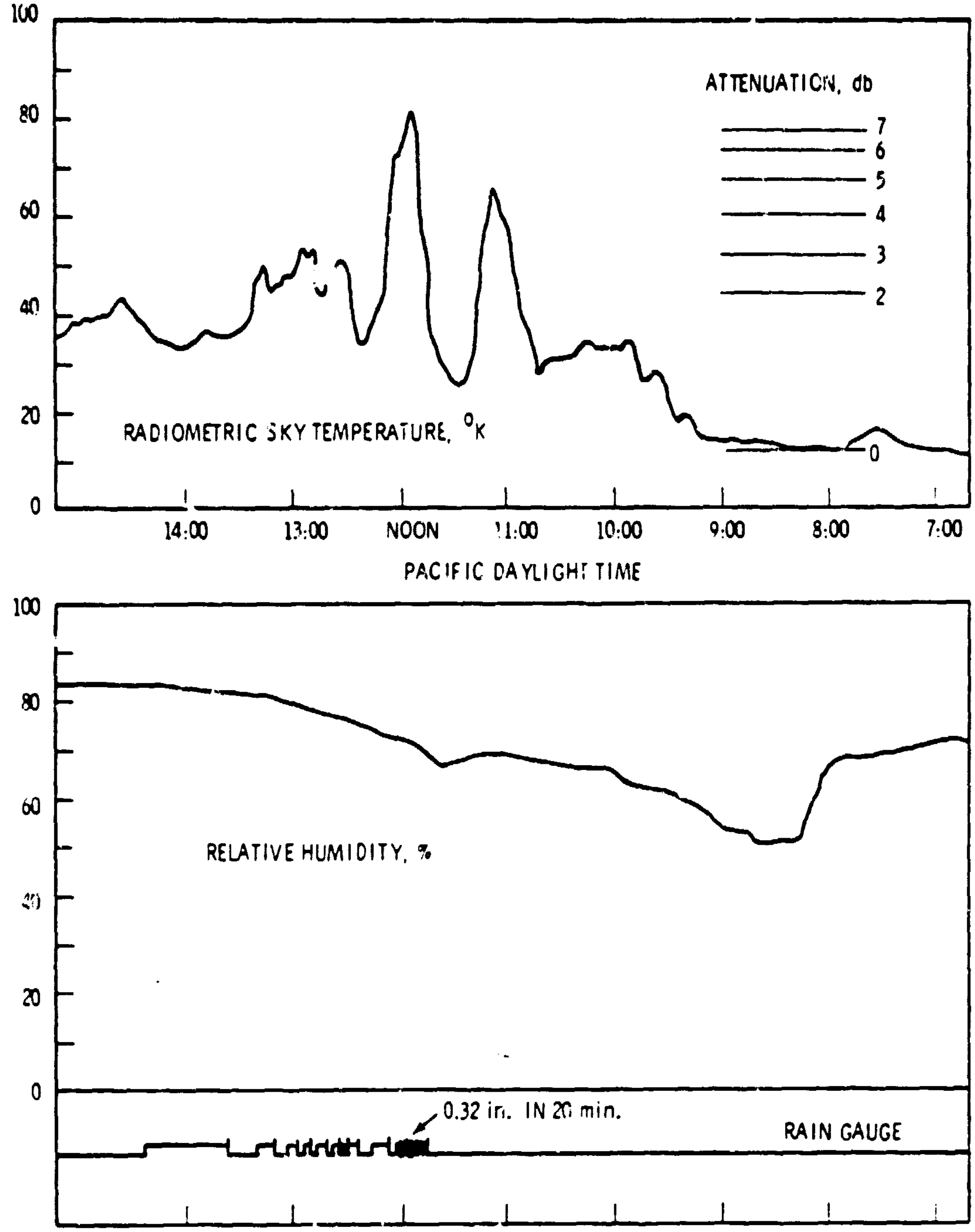


FIGURE 7. Radiometric Sky Temperature and Precipitation Intensity During the Storm of August 7, 1976

Figure 8 is a plot of atmospheric attenuation at 30° elevation angle inferred from radiometric sky temperature measure[illegible] versus measured precipitation intensity. Attenuations of almost 2 dB were measured in many cases, with no observed precipitation. In one case a hail storm produced only a trace (~0.01 in.) of local precipitation, although it was accompanied by 4.5 dB attenuation.

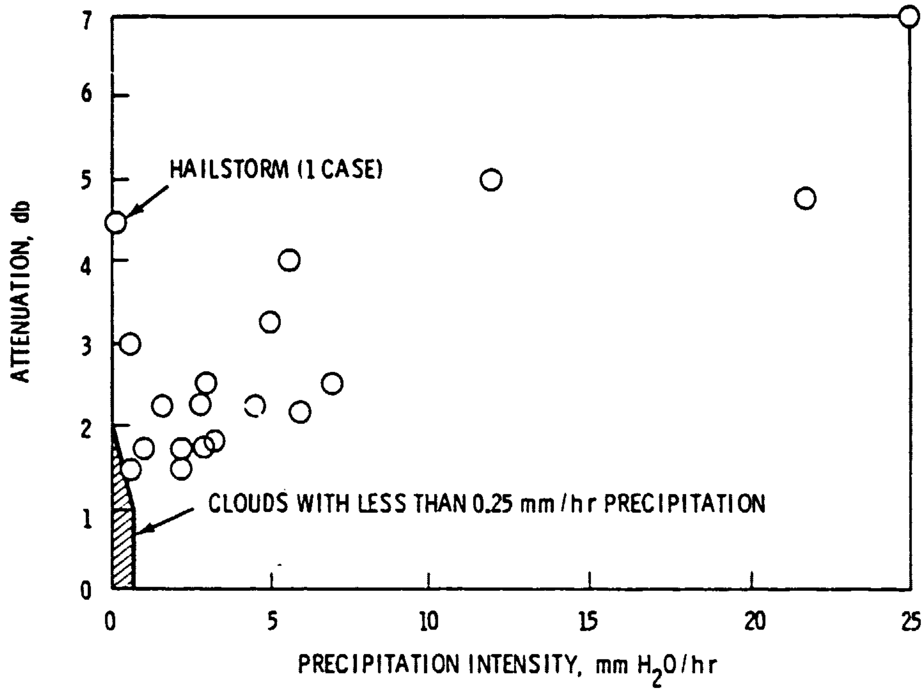


FIGURE 8. Attenuation Inferred from Radiometric Sky Temperature Versus Precipitation Intensity (each circle represents one occurrence)

Figure 9 is a plot of cumulative probability versus path attenuation based on the 5000 hours of data taken in 1976 after the radiometer was moved and excluding the anomalous event of early March. Since large attenuations are rare at this site, the statistical base for this curve is meager. The entire tail beyond 4 dB attenuation is based on a single event.

CONCLUSIONS

The data collected in this study are in general agreement with the attenuation versus rain intensity data of Haroules and Brown (G. G. Haroules and W. E. Brown, Journal of Geophysical Research, Vol. 74, No. 18, pp. 4453-4471, August 1969) if attenuation of 1 to 2 dB is allowed for clouds associated with precipitation and path lengths through the precipitation of 1 to 2 km are assumed. This indicates that rain intensities greater than 10 mm per hour would be required to produce attenuation greater than 5 dB on a 20 GHz

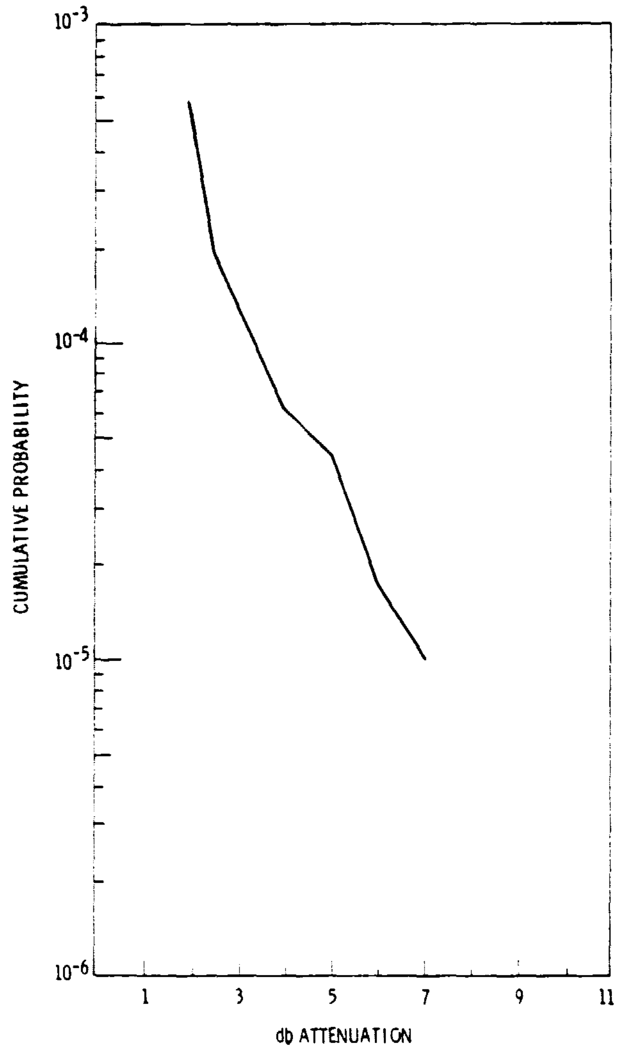


FIGURE 9. Cumulative Probability of Attenuation Based on Data Taken in 1976

Space-to-Earth path. Climatological data for the Hanford area (summarized in the Appendix) indicate that precipitation of this intensity occurs on the average

for 20 minutes	once in 2 years
for 1 hour	once in 5 years
for 2 hours	once in 50 years.

We thus expect that weather would interfere with 20 GHz satellite communications at this site for no more than a few hours per year, if antenna surfaces were kept clear of snow.

APPENDIX

SUMMARY OF CLIMATOGRAPHY OF THE HANFORD AREA WITH PARTICULAR ATTENTION TO PRECIPITATION

The Hanford Meteorology Station is approximately 12 km north of and 1 km lower than the Battelle Observatory site which is on Rattlesnake Mountain. The following text is abstracted from BNWL-1605, Climatography of the Hanford Area. The summarized data in the following pages is based on records for the period 1946-1970.

The Hanford Meteorology Station is situated on a plateau in south central Washington. The plateau slopes downward toward the Columbia River about 10 miles north of the station and upward to the foothills of the Rattlesnake Mountains about 10 miles south. Elevation of the station is 733 ft, which is roughly 300 ft above the Columbia River to the north. Both the Rattlesnake Mountains south and southwest of the station and the Yakima Ridge to the west rise to more than 3500 ft, while the Saddle Mountains beyond the Columbia River to the north rise to more than 2500 ft.

Greatly affecting the climate of the Hanford area, although not visible from the meteorology station, are the Cascade Mountains beyond Yakima to the west. Since Hanford is in the rain shadow of these mountains, precipitation totals only 6.25 in. annually. The 3 months November-through-January contribute 42% of this total, while the 3 months July-through-September contribute only 10%. There are only two occurrences per year of 24-hour amounts of 0.50 in. or more, while occurrences of 24-hour amounts of 1.00 in. or more number only four in the entire 25 years of record (1946-1970). One of these was the record storm of October 1-2, 1957, in which rainfall totaled 1.08 in. in 3 hours, 1.68 in. in 6 hours, and 1.88 in. in 12 hours. At the other extreme, there have been 81 consecutive days without measurable rain (June 22-September 10, 1968), 139 days with only 0.18 in. (June 22-November 7, 1967) and 172 days with only 0.32 in. (February 24-August 13, 1968).

About 45% of all precipitation during the months December-through-February is in the form of snow. However, only one winter in eight can expect an accumulation of as much as 6 in. on the ground. The average seasonal number of such days is five, although the 1964-65 winter had 35, 32 of which were consecutive.

Thunderstorms have been observed at the station in every month except the period November-through-January and one occurred at Richland (about 25 miles SE) on January 18, 1953. Although severe ones are rare, lightning strikes have occasionally ignited grass fires which burned thousands of acres of the Hanford project land and resulted subsequently in considerable wind erosion. The most notable of these occurred in August 1961, July 1963, and July 1970.

TABLE A-1. Averages and Extremes of Climatic Elements at Hanford

(BASED ON ALL AVAILABLE RECORDS TO AND INCLUDING THE YEAR 1970)

	TEMPERATURE (°F) 1912-1970 AVERAGES							TEMPERATURE (°F) 1912-1970 EXTREMES: DAILY MAXIMUM				DAILY MINIMUM			
	DAILY MAXIMUM	DAILY MINIMUM	MONTHLY	HIGHEST MONTHLY	YEAR	LOWEST MONTHLY	YEAR	RECORD HIGHEST	YEAR	RECORD LOWEST	YEAR	RECORD HIGHEST	YEAR	RECORD LOWEST	YEAR
Jan.	36.7	22.1	29.4	42.5	1953	12.1	1950	68	1968	-2	1950	51	1921	-23	1937+
Feb.	45.3	27.3	36.2	44.5	1958	21.6	1929	71	1928	-3	1950	55	1932	-23	1950
Mar.	56.3	33.6	45.2	49.5	1926	39.4	1955	83	1960	24	1948	54	1962	9	1955
Apr.	66.3	42.1	53.2	56.6	1934	47.5	1955	95	1934	41	1965	60	1956	12	1935
May	75.5	48.0	61.6	66.6	1947	56.9	1933	105	1936+	49	1918	70	1956	23	1954
June	83.2	55.5	69.4	75.4	1922	63.0	1953	110	1912	55	1966	81	1920	33	1933
July	91.8	61.0	76.4	81.8	1960	72.4	1963	115	1939	59	1966	82	1925	41	1935
Aug.	89.2	59.2	74.2	81.5	1967	69.8	1964	113	1961	63	1920	81	1961	40	1918
Sept.	79.6	50.8	65.2	71.7	1967	58.6	1926	102	1950	52	1934+	72	1955	25	1926
Oct.	65.3	42.8	53.1	55.9	1952	46.8	1930	92	1933	31	1935	50	1945+	9	1935
Nov.	48.6	31.5	40.5	46.0	1954+	31.3	1955	73	1934	14	1955	52	1954+	-1	1955
Dec.	39.2	26.0	32.6	42.0	1933	18.5	1919	66	1933	-3	1919	53	1933+	-27	1919
Year	64.8	41.6	53.1	81.8	July 1960	12.1	Jan. 1950	115	July 1939	-3	Feb. 1950+	82	July 1925	-27	Dec. 1919

	DEGREE DAYS (BASE 65°F) 1945-1970 TOTALS					PRECIPITATION (INCHES) 1912-1970 TOTALS							SNOW, ICE PELLETS (SLEET)						
	MEAN MONTHLY	MAXIMUM MONTHLY	YEAR	MINIMUM MONTHLY	YEAR	MEAN MONTHLY	MAXIMUM MONTHLY	YEAR	MINIMUM MONTHLY	YEAR	MAX. IN 24 HOURS	YEAR	MEAN MONTHLY	MAXIMUM MONTHLY	YEAR	MAX. IN 24 HOURS	YEAR	MAXIMUM DEPTH	YEAR
Jan.	1046	1660	1950	[illegible]	1953	0.93	2.47	1970	0.13	1962+	1.05	1948	5.2	23.4	1950	7.1	1954	12.0	1969
Feb.	778	1147	1956	576	1958	0.62	3.08	1940	T	1967+	1.24	1926	2.3	26.0	1916	5.2	1944	10.0	1969
Mar.	642	744	1955	476	1947	0.36	1.36	1957	0	1962+	0.54	1949	0.3	4.2	1951	2.2	1957+	2.3	1957
Apr.	362	522	1955	256	1967	0.40	1.22	1946	0	1933+	0.53	1951	T	T	1968+	T	1968+	0	----
May	153	255	1962	36	1947	0.45	1.71	1949	0	1951	0.55	1948+	T	T	1960	T	1960	0	----
June	36	90	1953	3	1958	0.57	2.92	1950	0	1919	1.50	1936	0	0	----	0	----	0	----
July	3	22	1955	0	1970+	0.16	0.81	1966	0	1919+	1.25	1942	0	0	----	0	----	0	----
Aug.	5	32	1960	0	1970+	0.19	1.15	1920	0	1955+	0.73	1914	0	0	----	0	----	0	----
Sept.	67	172	1970	13	1967	0.30	1.34	1947	T	1964+	0.82	1947	0	0	----	0	----	0	----
Oct.	373	479	1946	250	1952	0.58	2.72	1957	0	1917+	1.91	1957	T	0.3	1957	0.3	1957	0.3	1957
Nov.	746	1008	1955	567	1954	0.85	3.05	1926	T	1939+	0.75	1946	1.2	12.7	1955	4.5	1955	5.1	1946
Dec.	991	1224	1964	622	1957	0.86	2.53	1921	0.11	1946	1.00	1958	3.7	13.4	1955	5.4	1965	12.1	1964
Year	5267	1660	Jan. 1950	0	Aug. 1970+	6.25	3.08	Feb. 1940	0	Aug. 1955+	1.91	Oct. 1957	12.7	26.0	Feb. 1916	7.1	Jan. 1954	12.1	Dec. 1964

	WIND (MPH) 1945-1970 AVERAGES						PEAK GUST			RELATIVE HUMIDITY (%) 1946-1970 AVERAGES					1946-1970 EXTREMES			
	PREVAILING DIRECTION	MEAN MONTHLY SPEED	HIGHEST MONTHLY	YEAR	LOWEST MONTHLY	YEAR	SPEED	DIRECTION	YEAR	MEAN	HIGHEST MONTHLY	YEAR	LOWEST MONTHLY	YEAR	HIGHEST	YEAR	LOWEST	YEAR
Jan.	NW	6.3	9.6	1953	3.1	1955	65	S	1967	75.7	88.8	1960	60.0	1963	100	1970+	13	1963
Feb.	NW	7.0	9.4	1961	4.6	1963	63	SW	1965	69.9	86.9	1963	54.0	1967	100	1970+	14	1962
Mar.	WNW	8.4	10.7	1956	5.9	1954	70	SW	1956	55.8	65.9	1950	44.0	1965	100	1970+	12	1965+
Apr.	WNW	9.0	11.1	1959	7.4	1954	60	WSW	1959	46.7	64.5	1963	36.9	1966	100	1963+	9	1954
May	WNW	8.8	10.5	1965+	5.8	1957	71	SSW	1968	42.2	62.4	1948	31.2	1966	100	1964+	7	1953
June	WNW	9.2	10.7	1949	7.2	1950+	72	SW	1957	39.6	53.5	1950	30.0	1949	100	1967+	10	1964+
July	WNW	8.6	9.6	1963	6.6	1955	59	WSW	1968	31.8	40.5	1955	21.9	1959	97	1963	6	1951
Aug.	WNW	8.0	9.1	1966	6.8	1956	60	SW	1961	36.8	43.8	1968	24.5	1967	100	1959	7	1951
Sept.	WNW	7.5	9.2	1961	5.4	1957	65	SSW	1953	40.6	55.1	1959	33.9	1952	100	1962+	10	1962+
Oct.	WNW	6.7	9.1	1966	4.6	1952	63	SSW	1956	57.8	74.2	1962	42.5	1952	100	1969+	10	1952
Nov.	NW	6.2	7.9	1965	2.9	1958	68	SSW	1949	72.9	80.5	1956	66.1	1959	100	1970+	16	1959
Dec.	NW	6.0	8.3	1968	3.9	1963+	71	SW	1955	80.4	89.9	1963	69.0	1968	100	1970+	28	1964+
Year	WNW	7.6	11.1	Apr. 1959	2.9	Nov. 1958	72	SW	June 1957	54.0	89.9	Dec. 1963	21.9	July 1959	100	Dec. 1970+	6	July 1951

	SKY COVER(SCALE 0-10) 1946-1970 AVERAGES (SUNRISE TO SUNSET)					SOLAR RADIATION (LANGLEYS)* 1953-1970 AVG. DAILY TOTALS					1953-1970 EXTREME DAILY TOTALS			
	MONTHLY	HIGHEST MONTHLY	YEAR	LOWEST MONTHLY	YEAR	MONTHLY	HIGHEST MONTHLY	YEAR	LOWEST MONTHLY	YEAR	HIGHEST MONTHLY	YEAR	LOWEST MONTHLY	YEAR
Jan.	7.8	9.0	1969	4.3	1949	118	175	1962	68	1955	277	1969	16	1970
Feb.	7.4	8.9	1961	5.9	1966	206	236	1960	168	1954	422	1958	37	1970+
Mar.	6.7	7.9	1950	4.9	1965	342	368	1965	305	1951	562	1968	71	1963
Apr.	6.4	8.1	1963	3.7	1951	470	526	1959+	374	1963	691	1956	115	1970
May	5.8	7.7	1960	4.5	1969	571	634	1970	511	1962	752	1959	67	1962
June	5.2	7.0	1950	2.8	1961	625	648	1960	503	1953	809	1957	112	1965
July	2.7	4.5	1955	0.9	1953	659	700	1966+	548	1955	769	1966	190	1955
Aug.	3.3	5.9	1968	0.8	1955	551	613	1955	475	1968	721	1957	127	1959
Sept.	4.1	6.1	1959	2.5	1950	418	457	1961	354	1959	591	1970	61	1957
Oct.	5.9	7.7	1950	3.9	1952	262	296	1958	227	1956	476	1958	38	1962
Nov.	7.5	9.0	1965	6.2	1957	135	160	1957	97	1968	283	1957	14	1966
Dec.	8.1	9.2	1962	6.8	1954	91	116	1970	57	1968	135	1963	14	1964+
Year	5.9	9.2	Dec. 1962	[illegible]	Aug. 1955	371	700	July 1966+	57	Dec. 1968	809	June 1957	14	Dec. 1964+

NUMBER OF DAYS (1945-1970)**

	CLEAR					PTLY CLDY	CLOUDY					THUNDERSTORMS				
	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR
Jan.	4	13	1949	0	1955+	7	20	27	1964+	6	1949	0	0	----	0	----
Feb.	5	9	1963+	1	1959+	6	17	26	1958	10	1951+	#	1	1962	0	1970+
Mar.	7	12	1955+	2	1961+	9	15	22	1968	7	1948	#	1	1960+	0	1970+
Apr.	7	18	1951	1	1963	11	12	23	1963	3	1949	1	3	1948	0	1970+
May	8	18	1953	2	1960	12	11	19	1960	3	1949	2	7	1956	0	1965+
June	11	23	1961	3	1966	10	9	15	1957	3	1949	3	6	1948	0	1963+
July	21	27	1952	14	1955	7	3	8	1955	0	1967+	2	5	1958+	0	1960+
Aug.	19	30	1955	11	1968	6	4	13	1968	0	1969+	2	8	1953	0	1964+
Sept.	15	23	1967	8	1968	8	7	13	1959	2	1952+	1	4	1959	0	1970+
Oct.	10	16	1955	3	1960+	9	12	18	1956+	3	1956	#	1	1966+	0	1970+
Nov.	5	10	1957	1	1965+	6	19	24	1965+	12	1968	0	0	----	0	----
Dec.	3	7	1956	0	1967	7	21	28	1962	14	1965	0	0	----	0	----
Year	115	30	Aug. 1955	0	Jan. 1955+	100	150	28	Dec. 1962	0	Aug. 1969+	11	8	Aug. 1953+	0	----

	HEAVY FOG (VIS. 1/4 MI. OR LESS)					PRECIP 0.10 INCH OR MORE					SNOW 1.0 INCH OR MORE				
	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR
Jan.	6	14	1965	0	1949	3	8	1970	0	1962+	2	10	1950	0	1967+
Feb.	3	11	1963	0	1967+	2	5	1961+	0	1967+	1	4	1956+	0	1970+
Mar.	1	5	1951	0	1966+	2	8	1957	0	1968+	#	2	1957+	0	1970+
Apr.	#	1	1950	0	1970+	2	5	1969	0	1966+	0	0	----	0	----
May	#	1	1958	0	1970+	2	4	1967+	0	1966+	0	0	----	0	----
June	0	0	----	0	--	2	6	1962	0	1962+	0	0	----	0	----
July	0	0	----	0	----	1	3	1955	0	1970+	0	0	----	0	----
Aug.	#	1	1959	0	1970+	1	3	1955	0	1970+	0	0	----	0	----
Sept.	#	1	1957	0	1970+	1	5	1966	0	1970+	0	0	----	0	----
Oct.	1	6	1962	0	1970+	2	6	1962	0	1966+	0	0	----	0	----
Nov.	5	13	1965	0	1960	3	7	1966+	0	1967	#	5	1955	0	1970+
Dec.	8	17	1950	2	1968+	3	9	1964	0	1969+	2	6	1964	0	1966+
Year	24	17	Dec. 1950	0	----	24	9	Dec. 1964	0	Sept. 1970+	5	10	Jan. 1950	0	----

	NUMBER OF DAYS (1945-1970): 3" OR MORE SNOW ON GND.					PEAK GUST 40 MPH OR GREATER					NUMBER OF DAYS (1912-1970): MAX. TEMP. 90 OR ABOVE				
	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR
Jan.	3	23	1949	0	1967+	3	9	1953	0	1957+	0	0	----	0	----
Feb.	3	16	1950	0	1970+	2	9	1961+	0	1970+	0	0	----	0	----
Mar.	0	0	----	0	----	3	9	1956	1	1965+	0	0	----	0	----
Apr.	0	0	----	0	----	3	6	1959	0	1967+	#	4	1926	0	1970+
May	0	0	----	0	----	2	6	1951	0	1963+	3	11	1924	0	1965+
June	0	0	----	0	----	2	4	1970+	0	1967+	9	23	1960+	0	1953
July	0	0	----	0	----	1	4	1962+	0	1966+	21	29	1941	5	1963
Aug.	0	0	----	0	----	1	5	1951	0	1970+	18	29	1915	7	1948
Sept.	0	0	----	0	----	2	4	1951	0	1970+	5	16	1938	0	1970+
Oct.	0	0	----	0	----	2	6	1967	0	1957+	#	1	1933	0	1970+
Nov.	1	10	1955	0	1970+	2	5	1961+	0	1966+	0	0	----	0	----
Dec.	2	14	1955	0	1966+	3	8	1957+	0	1966+	0	0	----	0	----
Year	11	23	Jan. 1949	0	----	[illegible]	9	Jan. 1953	0	----	[illegible]	29	July 1941+	0	----

	MAX. TEMP. 100 OR ABOVE					MAX. TEMP. 32 OR BELOW					MIN. TEMP. 32 OR BELOW					MIN. TEMP. 0 OR BELOW				
	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR	MEAN MONTHLY	GREATEST MONTHLY	YEAR	LEAST MONTHLY	YEAR
Jan.	0	0	----	0	----	11	29	1937	0	1967+	28	31	1940+	9	1953	2	14	1950	0	1970+
Feb.	0	0	----	0	----	3	19	1936	0	1970+	22	28	1944+	5	1958	1	9	1929	0	1970+
Mar.	0	0	----	0	----	#	2	1960	0	1970+	16	25	1944+	6	1968+	0	0	----	0	----
Apr.	0	0	----	0	----	0	0	----	0	----	5	15	1935	0	1962+	0	0	----	0	----
May	#	1	1960+	0	1970+	0	0	----	0	----	#	3	1938	0	1966+	0	0	----	0	----
June	2	9	1970	0	1962+	0	0	----	0	----	0	0	----	0	----	0	0	----	0	----
July	7	18	1960+	0	1963+	0	0	----	0	----	0	0	----	0	----	0	0	----	0	----
Aug.	4	16	1942	0	1966+	0	0	----	0	----	0	0	----	0	----	0	0	----	0	----
Sept.	#	2	1955+	0	1970+	0	0	----	0	----	#	4	1953+	0	1970+	0	0	----	0	----
Oct.	0	0	----	0	----	#	2	1935	0	1970+	5	12	1916	0	1962+	0	0	----	0	----
Nov.	0	0	----	0	----	2	15	1955	0	1962+	17	30	1936	4	1949	#	1	1955+	0	1970+
Dec.	0	0	----	0	----	8	19	1914	2	1966+	26	31	1963+	14	1953	1	14	1919	0	1970+
Year	13	16	July 1960+	0	----	24	29	Jan. 1937	0	----	119	31	Dec. 1963+	3	----	4	14	Jan. 1950+	0	----

EXTREME AVERAGES OR TOTALS AND YEAR OR SEASON OF OCCURENCE

1912-1970 TEMPERATURE AVERAGES (°F)		
HIGHEST ANNUAL	56.2	1958+
LOWEST ANNUAL	50.2	1929
HIGHEST WINTER (D-J-F)	41.1	1933-34
LOWEST WINTER	24.2	1948-49
HIGHEST SPRING (M-A-M)	58.2	1947
LOWEST SPRING	48.0	1955
HIGHEST SUMMER (J-J-A)	78.2	1958
LOWEST SUMMER	70.3	1954
HIGHEST FALL (S-O-N)	56.6	1963
LOWEST FALL	45.6	1946
1912-1970 PRECIPITATION TOTALS (IN.)		
GREATEST ANNUAL	11.45	1950
LEAST ANNUAL	3.25	1967
SNOW, ICE PELLETS (SLEET) GREATEST SEASONAL	43.6	1915-16
LEAST SEASONAL	0.3	1957-58
1945-1970 WIND SPEED AVERAGE (mph)		
HIGHEST ANNUAL	8.3	1968+
LOWEST ANNUAL	6.3	1957
1946-1970 RELATIVE HUMIDITY AVERAGE (%)		
HIGHEST ANNUAL	57.9	1950+
LOWEST ANNUAL	49.4	1967
1946-1970 SKY COVER AVERAGES (SUNRISE TO SUNSET, SCALE 0-10)		
HIGHEST ANNUAL	6.4	1966
LOWEST ANNUAL	5.1	1949
1953-1970 SOLAR RADIATION AVERAGE DAILY TOTAL (LANGLEYS)		
HIGHEST ANNUAL	385	1957
LOWEST ANNUAL	357	1967
NUMBER OF DAYS		
CLEAR (0-3 TENTHS SKY COVER, SR TO SS): GREATEST ANNUAL (1946-70)	141	1951
LEAST ANNUAL (1946-70)	85	1946
CLOUDY (8-10 TENTHS SKY COVER, SR TO SS): GREATEST ANNUAL (1946-70)	182	1964+
LEAST ANNUAL (1946-70)	58	1969
THUNDERSTORMS: GREATEST ANNUAL (1945-70)	23	1948
LEAST ANNUAL (1945-70)	3	1969
HEAVY FOG (VIS. 1/4 MILE OR LESS): GREATEST SEASONAL (1945-70)	42	1950-51
LEAST SEASONAL (1945-70)	9	1945-49
PRECIPITATION 0.10 INCH OR MORE: GREATEST ANNUAL (1946-70)	39	1950
LEAST ANNUAL (1946-70)	10	1965
SNOW 1.0 INCH OR MORE: GREATEST SEASONAL (1946-70)	15	1955-56
LEAST SEASONAL (1946-70)	0	1957-58
3 IN. OR MORE SNOW ON GROUND: GREATEST SEASONAL (1946-70)	40	1964-65
LEAST SEASONAL (1946-70)	0	1960-61+
PEAK GUST 40 MPH OR GREATER: GREATEST ANNUAL (1945-70)	41	1962
LEAST ANNUAL (1945-70)	13	1958
MAX. TEMPERATURE 90 OR ABOVE: GREATEST ANNUAL (1912-70)	85	1960+
LEAST ANNUAL (1912-70)	37	1954
MAX. TEMPERATURE 100 OR ABOVE: GREATEST ANNUAL (1912-70)	32	1942
LEAST ANNUAL (1912-70)	1	1954
MAX. TEMPERATURE 32 OR BELOW: GREATEST SEASONAL (1912-70)	53	1955-56
LEAST SEASONAL (1912-70)	1	1937-38
MIN. TEMPERATURE 32 OR BELOW: GREATEST SEASONAL (1912-70)	141	1916-17
LEAST SEASONAL (1912-70)	75	1957-58
MIN. TEMPERATURE 0 OR BELOW: GREATEST SEASONAL (1912-70)	13	1949-50
LEAST SEASONAL (1912-70)	0	1969-70+

REFERENCE NOTES

* CALORIES/cm²

** SKY COVER AND PRECIPITATION OBSERVATIONS NOT BEGUN UNTIL 1946

\# LESS THAN 1/2

\+ ALSO ON EARLIER YEARS

LOCATION AND HISTORY

PRESENT LOCATION 25 MILES NW OF RICHLAND, WASHINGTON

LATITUDE 46°34' N, LONGITUDE 119°36' W   ELEVATION 733 FEET

OBSERVATIONS FROM 1912 TO 1944 WERE BY UNITED STATES WEATHER BUREAU COOPERATIVE OBSERVERS AT A SITE ABOUT 10 MILES ENE OF PRESENT LOCATION. SINCE 1944 OBSERVATIONS HAVE BEEN MAINTAINED ON A 24 HOUR-A-DAY BASIS BY THREE DIFFERENT AEC CONTRACTORS.

TABLE A.2. Monthly and Annual Averages and Extremes in Total Time with Precipitation Observed 1946-1970

	AVERAGES		GREATEST			LEAST		
MONTH	NO. OF HOURS	% OF TIME	NO. OF HOURS	% OF TIME	YEAR	NO. OF HOURS	% OF TIME	YEAR
JAN	96.4	13.0	212.0	28.5	1969	29.2	3.9	1949
FEB	56.7	8.4	106.8	15.9	1958	4.7	0.7	1967
MAR	37.1	5.0	135.2	18.2	1957	7.3	1.0	1968
APR	31.5	4.4	69.2	9.6	1953	1.8	0.2	1956
MAY	34.9	4.7	89.9	12.1	1948	4.8	0.6	1947
JUNE	33.4	4.6	80.8	11.2	1950	3.2	0.4	1949
JULY	9.6	1.3	38.2	5.1	1966	1.0	0.1	1958
AUG	13.5	1.8	61.7	8.3	1968	0.0	0.0	1955
SEPT	17.0	2.4	52.2	7.2	1959	1.3	0.2	1950
OCT	38.8	5.2	119.9	16.1	1947	3.6	0.5	1952
NOV	68.1	9.6	132.2	18.4	1955	21.4	3.0	1957
DEC	93.8	12.6	179.6	24.1	1963	31.5	4.2	1946
ANNUAL AVG	44.2	6.1	738.0 *	8.4	1950	355.4 *	4.1	1949

* ANNUAL EXTREMES

TABLE A-3. Average Return Period (R) and Existing Record (ER) for Various Precipitation Amounts and Intensity During Specified Time Periods at Hanford

(BASED ON EXTREME VALUE ANALYSIS OF 1947-69 RECORDS)

	AMOUNT (INCHES)							INTENSITY (INCHES PER HOUR)						
	TIME PERIOD							TIME PERIOD						
R (YEARS)	20 MIN	60 MIN	2 HRS	3 HRS	6 HRS	12 HRS	24 HRS	20 MIN	60 MIN	2 HRS	3 HRS	6 HRS	12 HRS	24 HRS
2	0.16	0.26	0.30	0.36	0.48	0.62	0.72	0.49	0.26	0.15	0.12	0.08	0.052	0.030
5	0.24	0.40	0.48	0.55	0.77	0.95	1.06	0.72	0.40	0.24	0.18	0.13	0.079	0.044
10	0.37	0.50	0.59	0.67	0.96	1.17	1.28	1.1	0.50	0.30	0.22	0.16	0.098	0.053
25	0.47	0.62	0.74	0.83	1.21	1.45	1.56	1.4	0.62	0.37	0.28	0.20	0.121	0.065
50	0.53	0.72	0.85	0.96	1.40	1.66	1.77	1.6	0.72	0.42	0.32	0.23	0.138	0.074
100	0.60	0.81	0.96	1.07	1.59	1.87	1.99	1.8	0.81	0.48	0.36	0.27	0.156	0.083
250	0.68	0.93	1.11	1.22	1.82	2.13	2.26	2.0	0.93	0.55	0.41	0.30	0.177	0.094
500	0.73	1.02	1.22	1.33	2.00	2.34	2.47	2.2	1.02	0.61	0.44	0.33	0.195	0.103
1000	0.80	1.11	1.33	1.45	2.20	2.55	2.68	2.4	1.11	0.67	0.48	0.37	0.212	0.112
ER	*	0.59	0.88	1.08	1.68	1.88	1.91	*	0.59	0.44	0.36	0.28	0.157	0.080
		6/12	10/1	10/1	10/1-2	10/1-2	10/1-2		6/12	10/1	10/1	10/1-2	10/1-2	10/1-2
DATE	--	1969	1957	1957	1957	1957	1957	--	1969	1957	1957	1957	1957	1957

* NO RECORDS HAVE BEEN KEPT FOR TIME PERIODS OF LESS THAN 60 MINUTES. HOWEVER, THE RAIN GAGE CHART FOR 6-12-69 SHOWS THAT 0.55 INCH OCCURRED DURING A 20-MINUTE PERIOD FROM 1835 TO 1855 PST. AN ADDITIONAL 0.04 INCH OCCURRED BETWEEN 1855 AND 1910 TO ACCOUNT FOR THE RECORD 60-MINUTE AMOUNT OF 0.59 INCH.

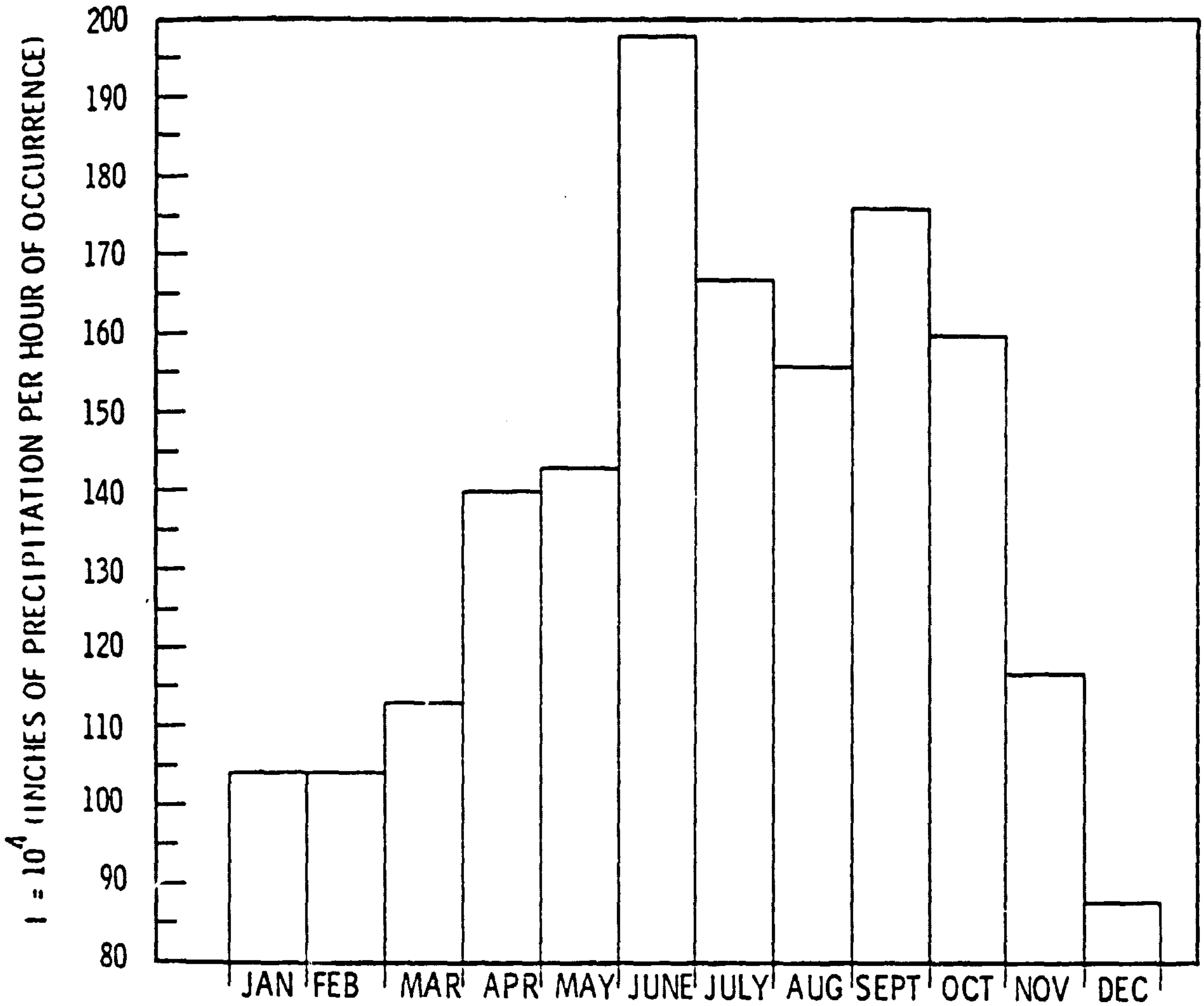
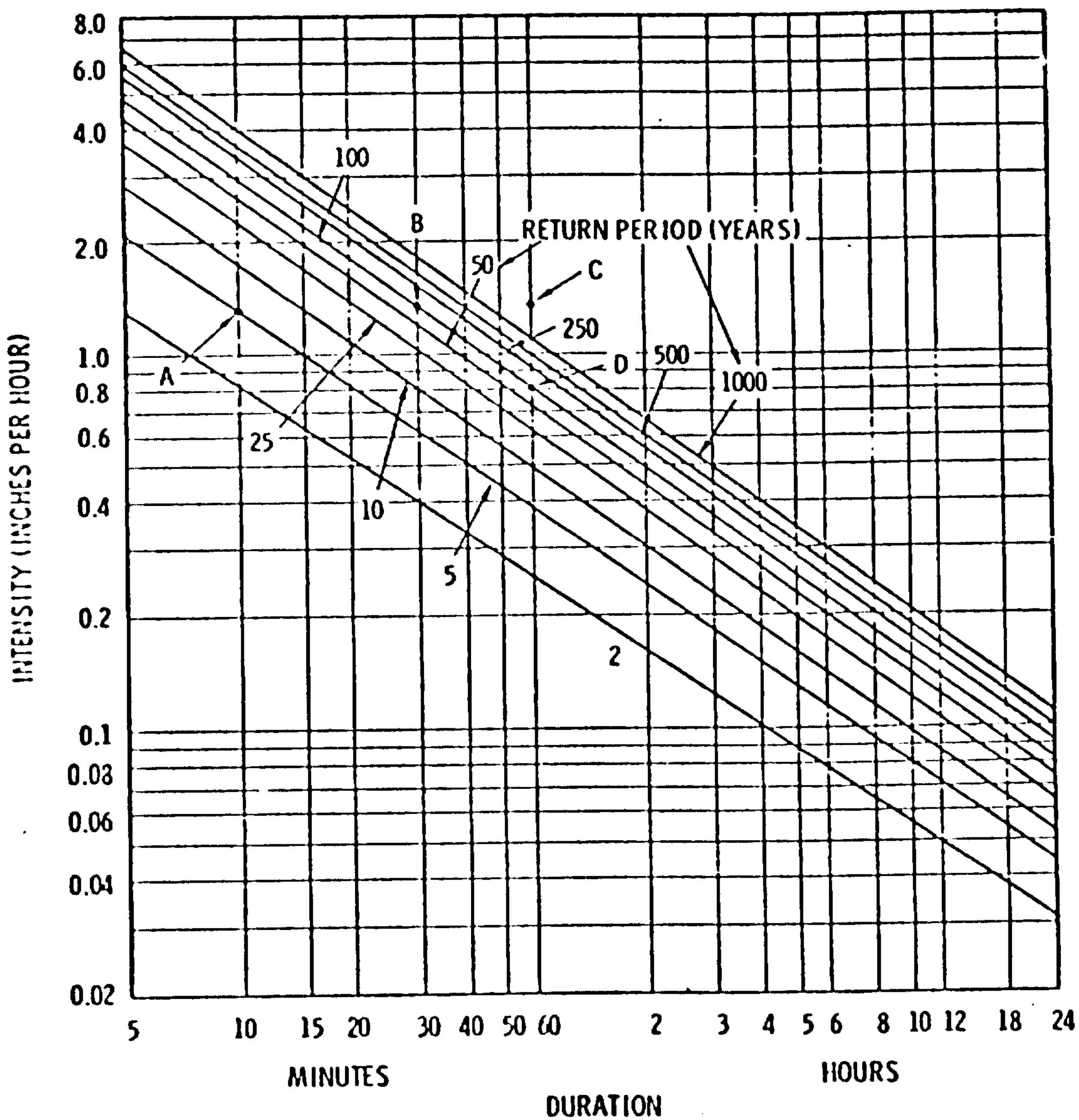


FIGURE A-1. Average Monthly Precipitation Intensity Factors Based on the Period 1946-1970



TO USE THIS CHART, SELECT ANY DESIRED RAINFALL INTENSITY AND DURATION AND READ FROM THE DIAGONAL LINES THE EXPECTED FREQUENCY OF SUCH INTENSITY AND DURATION. FOR EXAMPLE, RAINFALL INTENSITY OF 1.3 INCHES PER HOUR FOR 10 MINUTES CAN BE EXPECTED TO OCCUR, ON AVERAGE, ONCE EVERY 5 YEARS (POINT A). HOWEVER, SUCH INTENSITY CAN BE EXPECTED FOR 30 MINUTES DURATION ONLY ABOUT ONCE IN 100 YEARS (POINT B). THE RETURN PERIOD FOR THIS INTENSITY FOR 60 MINUTES DURATION IS GREATER THAN 1000 YEARS (POINT C).

THERE ARE, OF COURSE, VARIATIONS IN USE OF THE CHART. SUPPOSE, FOR EXAMPLE, IT IS DESIRED TO FIND THE "100-YEAR STORM" FOR 60 MINUTES. THIS IS 0.8 INCH (POINT D).

FIGURE A-2. Rainfall Intensity, Duration, and Frequency Based on the Period 1947-69 at Hanford